Normal metal to ferromagnetic superconductor tunneling

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We study the point-contact tunneling between a normal metal and a ferromagnetic superconductor. In the case of magnon-induced pairing the tunneling conductance is a continuous and smooth function of the applied voltage. For small values of the applied voltage the Ohm law holds. We show that one can obtain the magnetization and the superconducting order parameter from the tunneling conductance. In the case of paramagnon-induced superconductivity the tunneling does not depend on the magnetization. We argue that the tunneling experiment can unambiguously determine the correct pairing mechanism in the ferromagnetic superconductors.

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The discovery of unconventional superconductivity caused an explosive growth of activities in various fields of condensed-matter research, stimulating studies of the basic mechanisms leading to this phenomenon. The most direct way to identify the Cooper pairs is from measurements of their spin susceptibility, which can be determined by the Knight shift, from measurements of nuclear spin-lattice relaxation rate $1/T_1$, probed by nuclear magnetic resonance and nuclear quadrupole resonance, and by electron tunneling.

In conventional superconductors, the quasi-particles form Cooper pairs in a spin-singlet state which has zero total spin. The existence of the gap in the quasi-particle spectrum leads to unusual properties of the systems: i) The specific heat decreases exponentially at low temperature, as opposed to the linear temperature dependence in the Fermi liquid theory. ii)The normal metal superconductor tunneling experiments show that the electrons from the normal side of the junction can tunnel through and become an excited quasi-particle on the superconducting side if the applied voltage is larger then the gap[1]. All these properties are well understood on the basis of the BCS theory of superconductivity.

The discovery of superconductivity in a single crystal of UGe_2[2], $URhGe$[3] and $ZrZn_2$[4] revived the interest in the coexistence of superconductivity and ferromagnetism. The experiments indicate that the superconductivity is confined to the ferromagnetic phase, the ferromagnetic order is stable within the superconducting phase (neutron scattering experiments), and the specific heat anomaly associated with the superconductivity in these materials appears to be absent. The specific heat depends on the temperature linearly at low temperature.

At ambient pressure UGe_2 is an itinerant ferromagnet below the Curie temperature $T_c = 52K$, with low-temperature ordered moment of $\mu_s = 1.4\mu_B/U$. With increasing pressure the system passes through two successive quantum phase transition, from ferromagnetism to ferromagnetic superconductivity at $P \sim 10$ kbar, and at higher pressure $P_c \sim 16$ kbar to paramagnetism[2, 5]. At the pressure where the superconducting transition temperature is a maximum $T_{sc} = 0.8K$, the ferromagnetic state is still stable with $T_c = 32K$. The survival of bulk ferromagnetism below T_{sc} has been confirmed directly via elastic neutron scattering measurements[5]. The specific heat coefficient $\gamma = C/T$ increases steeply near 11 kbar and retains a large and nearly constant value[6].

Specifically, UGe_2 has strong spin orbit-interaction that leads to an unusually large magneto-crystalline anisotropy with an easy magnetization axis along the shortest crystallographic axis.

The ferromagnets $ZrZn_2$ and $URhGe$ are superconducting at ambient pressure with superconducting critical temperatures $T_{sc} = 0.29K$[4] and $T_{sc} = 0.25K$[5] respectively. $ZrZn_2$ is ferromagnetic below the Curie temperature $T_c = 28.5K$ with low-temperature ordered moment of $\mu_s = 0.17\mu_B$ per formula unit, while for $URhGe$ $T_c = 9.5K$ and $\mu_s = 0.42\mu_B$. The low Curie temperatures and small ordered moments indicate that compounds are close to a ferromagnetic quantum critical point.

We shall discuss two mechanisms of Cooper pairing in ferromagnetic metals: superconductivity induced by longitudinal spin fluctuations[7] and magnon exchange mechanism of superconductivity[8]. In the case of paramagnon induced superconductivity[7] the order parameters are spin parallel components of the spin triplet. The theory predicts that spin up and spin down fermions form Cooper pairs, and hence the specific heat decreases exponentially at low temperature. The phenomenological theories [9] circumvent the problem assuming that only majority spin fermions form pairs, and hence the minority spin fermions contribute the asymptotic of the specific heat. The magnon exchange mechanism of superconductivity was developed[8] to explain in a natural way the fact that the superconductivity in UGe_2, $ZrZn_2$ and $URhGe$ is confined to the ferromagnetic phase.The order parameter is a spin anti-parallel component of a spin-1 triplet with zero spin projection ($\uparrow\downarrow + \downarrow\uparrow$). The onset of superconductivity leads to the appearance of Fermi surfaces in the spin up and spin down momentum distribution functions. As a result, the specific heat depends on the temperature linearly, at low temperature.

During the last years tunneling spectroscopy has been applied to identify the pairing symmetry. The most basic idea of tunneling spectroscopy was first proposed by Bardeen[10] who introduced the tunnel Hamiltonian approximation for describing a tunnel junction. The con-

cept of the tunneling Hamiltonian[11] became universally adopted for the discussion of tunneling in superconductors. The idea is to write the Hamiltonian as a sum of three terms

$$H = H_L + H_R + H_T \tag{1}$$

The first two terms H_L and H_R are considered to be independent, expressed in terms of two independent sets of Fermi operators $c_{k,\sigma}, c^+_{k,\sigma}$ and $d_{q,\sigma}, d^+_{q,\sigma}$, where $\sigma = (\uparrow, \downarrow)$. Tunneling is caused by the term H_T

$$H_T = \sum_{k,q,\sigma} \left[t_{k,q} c^+_{k,\sigma} d_{q,\sigma} + t^*_{k,q} d^+_{q,\sigma} c_{k,\sigma} \right] \tag{2}$$

The tunneling matrix element $t_{k,q}$ describes the transfer of the particle through the junction. In this letter we focus our attention on the point contact case, therefore it is assumed $t_{k,q}$ to depend only on the wave vectors on the two sides "k" and "q". The tunneling takes place over a very narrow span of energies near the Fermi surfaces of the "left" and "right" systems, that is why it is an adequate approximation to treat the transfer rate $t_{k,q}$ as a constant which is evaluated at k_F and q_F ($t_{q_F,k_F} = t^*_{q_F,k_F} = t$).

We consider the tunneling process from a normal metal to a ferromagnetic superconductor. H_L is the Hamiltonian of the system of free spin 1/2 fermions with dispersion $\epsilon_k = \frac{k^2}{2m} - \mu$, $H_L = \sum\limits_{k,\sigma} \epsilon_k c^+_{k\sigma} c_{k\sigma}$, and H_R is the Hamiltonian for the ferromagnetic superconductor. For the magnon-induced superconductivity it has the form

$$\begin{aligned} H_R = & \sum_{k,\sigma} \epsilon_{k\sigma} d^+_{k\sigma} d_{k\sigma} + \\ & \sum_k \Delta_k \left[d_{k\uparrow} d_{-k\downarrow} + d_{k\downarrow} d_{-k\uparrow} + d^+_{-k\uparrow} d^+_{k\downarrow} + d^+_{-k\downarrow} d^+_{k\uparrow} \right] \end{aligned} \tag{3}$$

while for paramagnon-induced superconductivity it is

$$H_R = \sum_{k,\sigma} \epsilon_{k\sigma} d^+_{k\sigma} d_{k\sigma} + \frac{1}{2} \sum_k \Delta_k \left[d_{k\uparrow} d_{-k\uparrow} + d^+_{-k\uparrow} d^+_{k\uparrow} \right]. \tag{4}$$

In Eqs.(3,4) $\epsilon_{k\uparrow} = \frac{k^2}{2m} - \mu - H$ and $\epsilon_{k\downarrow} = \frac{k^2}{2m} - \mu + H$, where H is the energy of the Zeeman splitting, which is proportional to the low temperature ordered moment. There is a symmetry relation for the gap function Δ_k which follows from the anti-commutation of spin 1/2 fermions $\Delta_{-k} = -\Delta_k$. The gap has the form $\Delta_k = \Delta_0 \cos\theta_k$[7, 8].

The strong spin-orbit coupling in UGe_2 and $URhGe$ requires pseudo-spin technique[12] . The spin rotations, in that case, are accompanied by a rotation in momentum space. Hence if we consider tunneling process from a normal metal to a ferromagnetic superconductor, the tunneling Hamiltonian is invariant if and only if the tunneling matrix element is a constant. This approximation is widely accepted, but in our case it is crucial for the applicability of the tunneling Hamiltonian.

Next we calculate the current through the tunnel junction. It is defined as

$$I = -e \left\langle \frac{d}{d\tau} \sum_{k,\sigma} c^+_{k,\sigma} c_{k,\sigma} \right\rangle. \tag{5}$$

The tunneling current can be presented in the form

$$I = et \sum_{k,q,\sigma} \left[\ll d_{q\sigma}, c^+_{k\sigma} \gg_< (\tau,\tau) - \ll c_{k\sigma}, d^+_{q\sigma} \gg_< (\tau,\tau) \right] \tag{6}$$

where we have introduced the Green function in the Keldysh representation $\ll A, B^+ \gg_< (\tau_1, \tau_2) = i \langle B^+(\tau_2) A(\tau_1) \rangle$[13]. Let us consider first the magnon-induced superconductivity. We want to compute the tunneling current to the lowest order $\left(\sim t^2\right)$ in t[14]. To that goal, we use the equations of motions of the Green functions in Eq. (6) to cast the current into the form

$$\begin{aligned} I = & et^2 \sum_{k,q,\sigma} \int \frac{d\omega}{2\pi} [[\Sigma_{\sigma r}(q,\omega) - \Sigma_{\sigma a}(q,\omega)] G_{\sigma <}(k,\omega) - \\ & \Sigma_{\sigma <}(q,\omega) [G_{\sigma r}(k,\omega) - G_{\sigma a}(k,\omega)]] \end{aligned} \tag{7}$$

where

$$\begin{aligned} \Sigma_{\uparrow\mu}(q,\omega) &= u_q^2 A_{1\mu}(q,\omega) + v_q^2 A^+_{2\mu}(q,\omega), \\ \Sigma_{\downarrow\mu}(q,\omega) &= v_q^2 A^+_{1\mu}(q,\omega) + u_q^2 A_{2\mu}(q,\omega), \ \mu = r, a, <. \end{aligned} \tag{8}$$

Here

$$u_q^2 = \frac{1}{2} \left(1 + \frac{\epsilon_q}{\sqrt{\epsilon_q^2 + \Delta_q^2}} \right), \ v_q^2 = 1 - u_q^2. \tag{9}$$

The expressions for the retarded/advanced Green functions are given as follows

$$\begin{aligned} G_{\sigma r/a}(k,\omega) &= \left(\omega - \epsilon_k \pm i0^+\right)^{-1} \\ A_{lr/a}(q,\omega) &= \left(\omega - E_{lq} \pm i0^+\right)^{-1}, \ l = 1, 2 \end{aligned} \tag{10}$$

and $A^+_{lr/a}(q,\omega) = -A^*_{la/r}(q,-\omega)$. The quasiparticle energies are

$$E_{1q} = -H - \sqrt{\epsilon_q^2 + \Delta_q^2}, \tag{11}$$

$$E_{2q} = H - \sqrt{\epsilon_q^2 + \Delta_q^2}. \tag{12}$$

The distribution Green function is defined as

$$G_{\sigma <}(k,\omega) = -f_{\mathrm{FD}}(\omega) \left[G_{\sigma r}(k,\omega) - G_{\sigma a}(k,\omega) \right], \tag{13}$$

$f_{\mathrm{FD}}(\omega)$ is the Fermi-Dirac function and likewise for $A_{l<}, l = 1, 2$. Next we convert the sums over the wave vectors into integrals over the corresponding energies by introducing the density of states for the left-hand and the right-hand side of the junction. We consider the simplest possibility of constant density of states, that is, we do not take into account the finite band-width effects.

This choice allows us to obtain analytical results in the zero-temperature case. The expression for the tunneling current is obtained in the form:

I) If $\Delta_0 \leq 2H$

$$\frac{I}{I_0} = \begin{cases} \frac{\pi}{2}\left(x_+^2 - x_-^2\right), & 0 \leq eV \leq \Delta_0 - H \\ \frac{\pi}{2}\left(x_+^2 - x_-^2\right) - f\left(x_+\right), & \Delta_0 - H \leq eV \leq H \\ \frac{\pi}{2}\left(x_+^2 + x_-^2\right) - f\left(x_+\right), & H \leq eV \leq \Delta_0 + H \\ \frac{\pi}{2}\left(x_+^2 + x_-^2\right) - f\left(x_+\right) - f(x_-), & eV \geq \Delta_0 + H \end{cases} \tag{14}$$

II) If $\Delta_0 \geq 2H$

$$\frac{I}{I_0} = \begin{cases} \frac{\pi}{2}\left(x_+^2 - x_-^2\right), & 0 \leq eV \leq H \\ \frac{\pi}{2}\left(x_+^2 + x_-^2\right), & H \leq eV \leq \Delta_0 - H \\ \frac{\pi}{2}\left(x_+^2 + x_-^2\right) - f\left(x_+\right), & \Delta_0 - H \leq eV \leq \Delta_0 + H \\ \frac{\pi}{2}\left(x_+^2 + x_-^2\right) - f\left(x_+\right) - f(x_-), & eV \geq \Delta_0 + H \end{cases} \tag{15}$$

where $I_0 = \pi e t^2 \rho_N^{(L)} \rho_N^{(R)} \Delta_0, x_\pm = \left(eV \pm H\right)/\Delta_0, f(x) = x^2 \tan^{-1}\sqrt{x^2-1} - \sqrt{x^2-1}$ and $\rho_N^{(L,R)}$ is the density of states in the left-hand/right-hand side of the junction. Also, we calculated the dynamical conductance $g = dI/dV$. The expression for it is given by

I) If $\Delta_0 \leq 2H$

$$\frac{g}{g_0} = \begin{cases} \frac{\pi H}{\Delta_0}, & 0 \leq eV \leq \Delta_0 - H \\ \frac{\pi H}{\Delta_0} - g\left(x_+\right), & \Delta_0 - H \leq eV \leq H \\ \frac{\pi eV}{\Delta_0} - g\left(x_+\right), & H \leq eV \leq \Delta_0 + H \\ \frac{\pi eV}{\Delta_0} - g\left(x_+\right) - g(x_-), & eV \geq \Delta_0 + H \end{cases} \tag{16}$$

II) If $\Delta_0 \geq 2H$

$$\frac{g}{g_0} = \begin{cases} \frac{\pi H}{\Delta_0}, & 0 \leq eV \leq H \\ \frac{\pi eV}{\Delta_0}, & H \leq eV \leq \Delta_0 - H \\ \frac{\pi eV}{\Delta_0} - g\left(x_+\right), & \Delta_0 - H \leq eV \leq \Delta_0 + H \\ \frac{\pi eV}{\Delta_0} - g\left(x_+\right) - g(x_-), & eV \geq \Delta_0 + H \end{cases} \tag{17}$$

where $g_0 = 2\pi e^2 t^2 \rho_N^{(L)} \rho_N^{(R)}$ and $g\left(x\right) = x \tan^{-1}\sqrt{x^2-1}$.

The results for both the tunneling current and the differential conductance are shown in Fig. 1 and Fig. 2. The most important feature of the tunneling conductance is that it is a continuous and smooth function of the applied voltage and does not show any discontinuities at the gap edges that are characteristics of the tunneling in which conventional superconductors are involved. Also, the tunneling current is non-zero when $eV \leq \Delta_0$. One observes that for small values of the applied voltage I depends linearly on it, that is, the Ohm law holds. This behavior is attributed to the existence of a Fermi surface in this model[8]. Another important feature to be pointed out is that the magnetization which is included in the Zeeman splitting energy H can be measured in a tunneling experiment. When $\Delta_0 \leq 2H$, the differential conductance is constant for $eV \leq \Delta_0 - H$, the minimum is located at $eV = H$ and the maximum is at $eV = \Delta_0 + H$ [Fig. 2, the solid curve]. In the case of $\Delta_0 \geq 2H$, g exhibits ohmic behavior for $eV \leq H$ and the two maximums are at $\Delta_0 - H$ and $\Delta_0 + H$ [Fig. 2, the short-dashed curve]. Thus, for any value of the microscopic parameters one can deduce the values of both Δ_0 and H from the tunneling conductance.

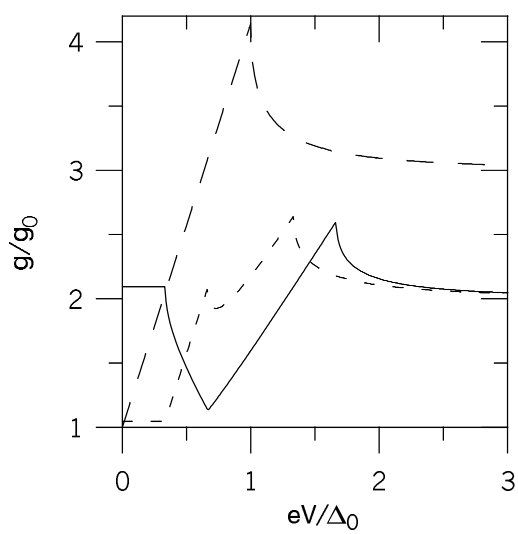

FIG. 2: The differential conductance as a function of the applied voltage in the case: i) magnon-induced superconductivity for $\Delta_0 = 1.5H$ (solid line) and $\Delta_0 = 3H$ (short-dashed line); ii) paramagnon-induced superconductivity (long-dashed line).

Let us consider now the paramagnon-induced superconductivity. In this case, the tunneling current is a sum of two terms $I = I_N + I_{SC}$ where I_N is the normal current due to the unpaired band of down-spin electrons and I_{SC} is the current of the superconducting up-spin electrons.

The explicit expressions for them are written as

$$I_N = et^2 \sum_{k,q} \int \frac{d\omega}{2\pi} [[D_{\downarrow r}(q,\omega) - D_{\downarrow a}(q,\omega)]\, G_{\downarrow <}(k,\omega) - D_{\downarrow <}(q,\omega)\,[G_{\downarrow r}(k,\omega) - G_{\downarrow a}(k,\omega)]], \tag{18}$$

and

$$I_{SC} = et^2 \sum_{k,q} \int \frac{d\omega}{2\pi} [[\Sigma_r(q,\omega) - \Sigma_a(q,\omega)]\, G_{\uparrow <}(k,\omega) - \Sigma_<(q,\omega)\,[G_{\uparrow r}(k,\omega) - G_{\uparrow a}(k,\omega)]], \tag{19}$$

where

$$\Sigma_\mu(q,\omega) = \widetilde{u}_q^2 A_\mu(q,\omega) + \widetilde{v}_q^2 A_\mu^+(q,\omega),\ \mu = r, a, < . \tag{20}$$

The retarded/advanced Green function are given by $D_{\downarrow r/a}(q,\omega) = (\omega - \epsilon_{q\downarrow} \pm i0^+)^{-1}, A_{r/a}(q,\omega) = (\omega - E_q \pm i0^+)^{-1}$ and the distribution Green functions are defined as above. The quasiparticle energy is

$$E_q = \sqrt{\epsilon_{q\uparrow}^2 + \Delta_q^2}. \tag{21}$$

Also,

$$\widetilde{u}_q^2 = \frac{1}{2}\left(1 + \frac{\epsilon_{q\uparrow}}{E_q}\right), \qquad \widetilde{v}_q^2 = \frac{1}{2}\left(1 - \frac{\epsilon_{q\uparrow}}{E_q}\right). \tag{22}$$

With the same assumptions as above the tunneling currents are obtained in the form

$$I_N = 2I_0 eV/\Delta_0 \tag{23}$$

$$I_{SC} = 2I_0\left[\frac{\pi}{2}\left(\frac{eV}{\Delta_0}\right)^2 - f\left(\frac{eV}{\Delta_0}\right)\theta\left(eV - \Delta_0\right)\right]. \tag{24}$$

Unlike the case of magnon-induced superconductivity the current does not depend on the Zeeman splitting energy. The corresponding expression for the differential conductance is cast into the form

$$g = g_0\left[1 + \pi\frac{eV}{\Delta_0} - 2g\left(\frac{eV}{\Delta_0}\right)\theta\left(eV - \Delta_0\right)\right]. \tag{25}$$

The results for the tunneling current and the differential conductance are shown in Fig. 1 and Fig. 2 (the long-dashed-line), respectively. One sees that g has no ohmic behavior and has only one maximum located at Δ_0. Thus, a tunneling experiment can very easily determine the correct pairing mechanism in the ferromagnetic superconductors.

Point-contact tunneling between normal metal and superconductor is one of the best probes for analyzing the energy gap of superconductors. Measurements of tunneling current yield valuable information on the symmetry of the order parameter which in turn is essential for understanding the mechanism of superconductivity. Our results differ from what we expect for the conventional superconductors in many aspects. Perhaps the most striking difference is the nonzero conductance inside the superconducting gap. The tunneling conductance is a continuous and smooth function of the applied voltage. For

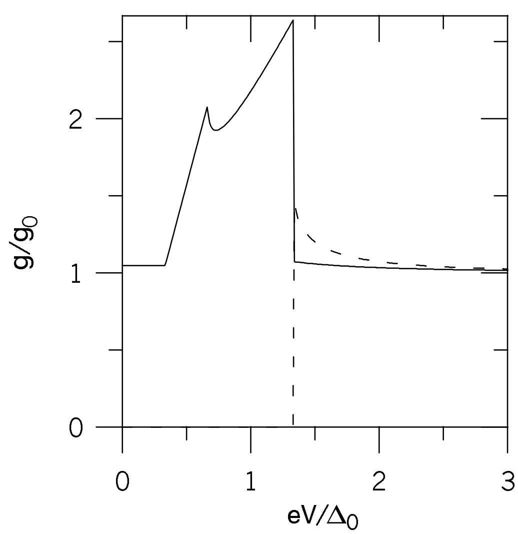

FIG. 4: Bogoliubov quasiparticle contribution to the differential conductance in the case of magnon-induced superconductivity for $\Delta_0 = 3H$: quasiparticle with energy E_{1q} [Eq. (11)] (short-dashed line) and quasiparticle with energy E_{2q} [Eq. (12)] (solid line).

small values of the applied voltage I depends linearly on it, that is, the Ohm law holds(Fig1). The main focus in the present paper is the evidence that the origin of this behavior is the existence of a Fermi surface in the superconducting phase. It was experimentally observed [4, 5] that the specific heat depends on the temperature linearly at low temperature. This means that the superconducting state is strongly gapless with a Fermi surface. Our theoretical prediction suggests that the tunneling experiment could give another independent verification of the surviving of the Fermi surface in the superconducting state.

We consider two pairing mechanisms - magnon - and paramagnon- induced superconductivity[7, 8]. In the case of magnon induced superconductivity the differential conductance exhibits ohmic behaviour at low voltages for any value of the microscopic parameters, and has two extreme points which determine the gap and the Zeeman splitting. Unlike this, the tunneling current, in the case of paramagnon-induced superconductivity, does not depend on the Zeeman splitting energy, the differential conductance has no ohmic behavior, and the only local maximum determines the gap.

The contribution of the Bogoliubov quasiparticles to the differential conductance is shown in Fig. 3 (for $\Delta_0 = 1.5H$) and in Fig. 4 (for $\Delta_0 = 3H$) in the case of magnon-induced superconductivity. From Eqs. (11,12) it can easily be established that there is a gap $\Delta_0 + H$ in the quasiparticle energy E_{1q} while the quasiparticle with energy E_{2q} is a gapless excitation with a Fermi surface[8]. As a result, the contribution of the first quasiparticle to the differential conductance shows typical behaviour well known for gapped superconductors [Figs. 3 and 4, the short-dashed line] and all important features in g we have already pointed out are due to the second quasiparticle [Figs 3 and 4, the solid lines]. Namely, the ohmic part in the differential conductance at low voltage bias reflects the gapless nature with a Fermi surface of this quasiparticle. The ferromagetic superconductors are anisotropic. The different symmetries of the order parameter correspond to different anisotropies, respectively to different Fermi surfaces.As a consequence, calculating the tunneling current and the differential conductance and averaging over the Fermi surface we obtain different expressions for the different Cooper pairing mechanisms.

It is important to compare our results with the results in the case of isotropic s-wave superconductors. At zero magnetic field the energies of the Bogoliubov quasiparticles are degenerate and there is only one peak in the quasiparticle density of states. Correspondingly, there is only one peak in the differential conductance. The effect of the magnetic field is to lift this degeneracy. The quasiparticle peak in the density of states splits in two peaks and as a result two peaks appear in the differential conductance with each peak coming from a quasiparticle with a given spin (up or down)[15, 16].

In the case of magnon-induced superconductivity the quasiparticle spectrum is not degenerate too. The two extrema in the differential conductance result from a complicated averaging over the Fermi surface and reflect the symmetry of the superconducting order parameter, respectively the mechanism of the superconductivity.

In the case of paramagnon-induced superconductivity there is one gapped excitation (21) which gives the only peak in the differential conductance. The other excitation is a free spin-down electron which is responsible for the linear in the bias voltage part of the tunneling current (23).

It is known that in the case of anisotropic pairing zero-energy bound states can exist [17]. They will modify the low-voltage behaviour of the differential conductance. The inclusion of these states would require modification of our approach. The results we have obtained will be changed at low voltages. However, the non-zero differential conductance at zero voltage is a direct consequence of the existence of a Fermi surface in the ferromagnetic superconductors. This behaviour will not be changed qualitatively when the zero-energy bound states are taken into account. The rest of out findings should apply in this case because they refer to features in the differential conductance at voltages of the order of the superconducting order parameter. The evident difference between the tunneling processes involving magnon-induced superconductivity and those involving paramagnon-induced superconductivity suggests that tunneling experiment could be crucial for understanding the mechanism of ferromagnetic superconductivity.

The ferromagnetic superconductivity was seen only in samples with small normal-state residual electrical resistivity $\rho_0 = 2\mu\Omega\mathrm{cm}$[3, 4]. This means that the impurity concentration is very low. Therefore, if the impurities are taken into account they will only slightly modify the low-voltage behaviour of the tunneling differential conductance.

The tunneling differential conductance in the case of s-wave superconductors in an external magnetic field has been measured long ago [15]. It shows different behavior for different values of the magnetic field [Fig. 1 in Ref.[15]], that is, the tunneling current measurements are sensitive to the quasiparticle spectrum of the system in the magnetic field. This fact demonstrates that the experiments can in principle distinguish the different behavior we predict for the two pairing mechanisms.

Our results differ, as well, from the calculations of the tunneling conductance in the case when spin-triplet superconductivity of different kind is considered[18]. This demonstrates that by means of tunneling experiments the symmetry of different p-wave superconductors can be established. This is an additional support for our efforts to distinguish the magnon and paramagnon mechanisms of FM superconductivity.

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